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## STABILITY CRITERIA FOR STRATOCUMULUS-TOPPED BOUNDARY LAYERS EVALUATED THROUGH CONDITIONAL SAMPLING OF TURBULENCE ELEMENTS

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### 1. INTRODUCTION

Low-level marine stratocumulus (MSc) clouds that form in the subtropics off the western coasts of major continents are a climatically important feature of the planetary boundary layer, because of their strong influence on the earth's radiation budget and on atmosphere-ocean coupling. The interactions of turbulence, radiation, phase change, and cloud microphysics in MSc provide an interesting and challenging problem in atmospheric physics. Although the conditions that favor the formation of MSc are large in scale (subsidence associated with subtropical highs and cool ocean surface temperatures produced by coastal upwelling), the stability and character of MSc depends on the small-scale turbulence structure that controls the vertical transports between the surface and cloud layers and the mixing across the capping inversion.

One small-scale process that has been proposed as important in the breakup of stratocumulus is cloud-top entrainment instability or CTEI. Under some conditions certain mixtures of cloud layer and entrained air may become negatively buoyant through the evaporation of cloud water droplets. The sinking of these parcels becomes a source of kinetic energy for the cloud layer; this energy can produce, it was proposed, accelerated entrainment and cloud breakup. A criterion for CTEI, based on the magnitude of the changes in thermodynamic quantities across the inversion, was originally proposed by Lilly (1968) and later refined by Randall (1980) and Deardorff (1980). However, it has been widely observed that this criterion is not obeyed in nature (see Kuo and Schubert, 1988). MSc decks are observed to persist when CTEI indicates they should be unstable, and cloud decks may break up for reasons other than CTEI.

Another process that may play a role in MSc break up is when the cloud layer becomes disconnected from its moisture source at the surface. Fallout and subsequent evaporation of drizzle may lead to the formation of a stable layer below cloud base. If the surface buoyancy flux is weak, this stable layer will prevent the upward flux of moisture into the cloud layer. It is also possible for MSc to become decoupled during the day when solar heating stabilizes the cloud layer.

The purpose of the present work is to examine the small-scale properties of MSc clouds for evidence of the processes affecting cloud stability. The knowledge gained through such studies will help in the development of physical models and parametrizations for these clouds.

### 2. DATA

The data used in this study were gathered during the First

ISCCP (International Satellite Cloud Climatology Project) Regional Experiment, or FIRE, field program which took place off the California coast in June and July of 1987. Here we will focus on one day, 7 July, during which the NCAR Electra research aircraft flew back and forth across the edge of an MSc layer. The low-level flow was NNW, approximately parallel to the boundary between solid MSc to the east and clear conditions to the west. Thus the circumstance was not one in which an MSc deck evolved as it was advected downstream. Nevertheless, it is instructive to compare the results for the cloudy and clear regions. In between these regions the cloud field was broken, with variable coverage by small cumulus. This will be referred to as the transitional region.

Four turbulence measuring legs were flown on 7 July, all approximately east-west or normal to the mean wind. The first leg was flown at 50 m to measure the fluxes near the surface. The next leg was at 360 m, just below cloud base. This was followed by a leg at 580 m which was about 100 m below cloud top. After some additional maneuvers, the 50-m leg was repeated. During the 2.5 hrs between the first and second 50-m legs, the cloud boundary had shifted about 30 km to the east.

Each flight leg was divided into three segments for analysis: cloudy, transitional, and clear. These divisions were based on observers' notes and lidar records and were provided by Boers (1989, personal communication). Results from the two 50-m legs will sometimes be averaged and at other times shown separately.

### 3. MEAN CONDITIONS

Data from the initial descent into the region is shown in Fig. 1. A 200 m thick cloud layer existed below a strong inversion at 700 m. There was a large jump in ozone across the inversion, making  $O_3$  useful for studying entrainment. Other soundings taken during the mission all showed a strong inversion but had variable structure above.

The buoyancy flux profiles for clear, transitional, and cloudy regions are shown in Fig. 2. The two 50 m legs for each region have been averaged together. Surface fluxes decreased going from west to east, clear to cloudy, as the surface temperature decreased. The opposite behavior occurred near cloud top, with the clear region showing a negative value and the cloudy region showing the largest positive value. The smallest buoyancy fluxes in all three regions were found near cloud base. In comparison to the cloudy region, the cloud base flux in the transitional region was a much smaller fraction of the respective surface flux. An interpretation of these profiles is given in Section 5.

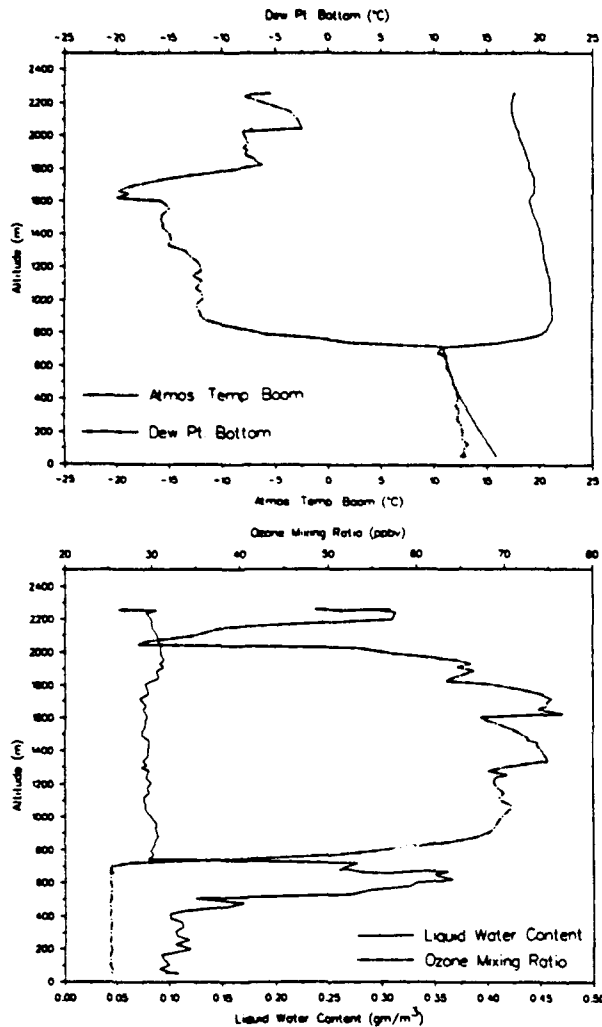


Fig. 1. Sounding made in cloudy region. a) air temperature and dewpoint. b) ozone mixing ratio and cloud liquid water. The bias in the LWC measurement has not been corrected for.

#### 4. METHODOLOGY

To obtain information on the turbulent elements of the flow we employed a conditional sampling technique based on an indicator function. The indicator function was set to +1 or -1 when the vertical velocity exceeded predetermined positive or negative thresholds. Other variables were sampled based on this indicator function and conditional averages were computed. Prior to determining the indicator function all variables were linearly detrended and a high pass filter was applied to remove fluctuations greater than about 8 km in length. As done in previous studies (e.g. Khalsa and Greenhut, 1985), the thresholds were based on the one-sided variances of vertical velocity. Also, no change of state that lasted less than 0.2 sec was allowed.

The updrafts and downdrafts identified by this method were further classified by their conditionally averaged temperature and moisture perturbations. This is particularly useful when there are two or more distinct types of drafts coexisting at a given level.

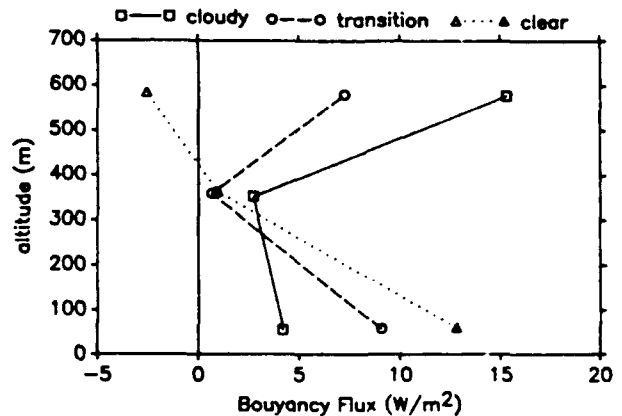


Fig. 2. Buoyancy flux profiles for the three regions. Fluxes from the two 50 m legs have been averaged.

#### 5. RESULTS

##### 5.1 Mean Draft Characteristics

We first examine selected properties of updrafts and downdrafts for the three regions, independent of thermodynamic classification. This provides an overview of the three regions and allows comparison with previous studies.

Event size is shown in Fig. 3. The largest drafts occur at cloud base, the smallest near the surface. In the cloudy region, downdraft intersection length at cloud base is 88 m compared to 73 m for updrafts. The fraction of record occupied by downdrafts (not shown) decreases with height in the clear region, is maximum at cloud base in the transitional region and increases with height in the cloudy region.

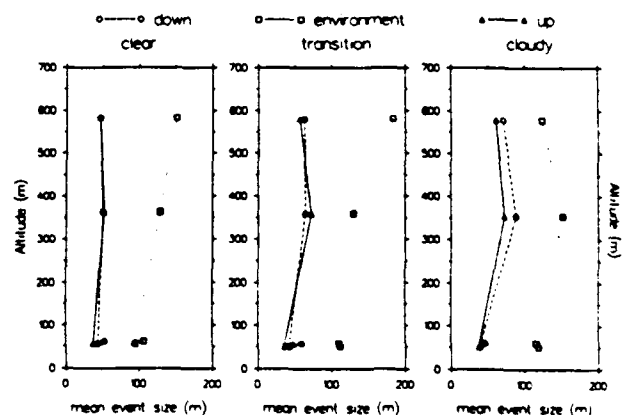


Fig. 3. Mean event size for the three regions.

The temperature perturbation,  $T'$ , of updrafts in the clear region is positive near the surface and negative at the upper two levels (Fig. 4). In the transitional and cloudy regions, updraft  $T'$  is positive for the first 50 m leg and negative for the second. In both areas  $T'$  is negative near cloud base and positive near cloud top. In the clear region downdrafts are warm at the uppermost level while in the cloudy region they are cool. Air entrained from above the inversion will be relatively warm in the clear region while evaporative or radiative cooling could explain the  $T' < 0$  for downdrafts in the cloudy region. The near-zero value of  $T'$  for downdrafts in the transitional region may result from a combination of the clear and cloudy processes.

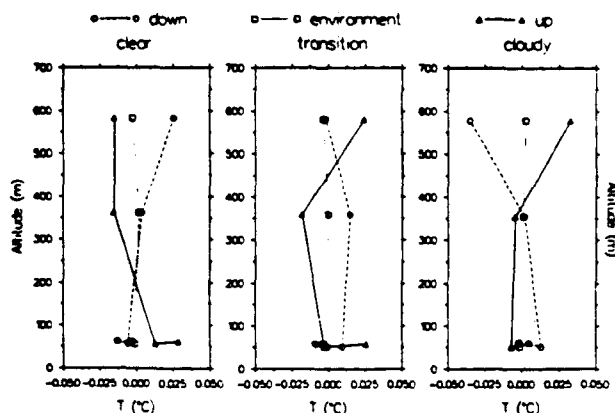


Fig. 4. Temperature perturbation for updrafts, downdrafts and the environment. Data from the two 50 m legs is shown separately. The second 50 m leg is slightly lower in altitude than the first.

Two conditions are observed at all three levels for all three regions. Updrafts are relatively moist ( $q' > 0$ ) and downdrafts are relatively dry ( $q' < 0$ ). Also, all updrafts carry a negative velocity perturbation in the direction of the mean wind ( $u' < 0$ ) and all downdrafts carry positive  $u'$ , in accordance with the mean wind shear.

Near cloud top all downdrafts have positive  $O_3'$  (not shown). In the transitional and cloudy regions updrafts at cloud have large  $O_3'$  deficits but in the clear region  $O_3'$  near cloud top is near zero. The explanation for this is that on the clear side a large number of the updrafts near the inversion were composed of positively buoyant air with  $O_3' > 0$  that had been entrained downward across the inversion and had subsequently turned back up. A nearly equal number of updrafts were sampled that contained air from lower in the boundary layer

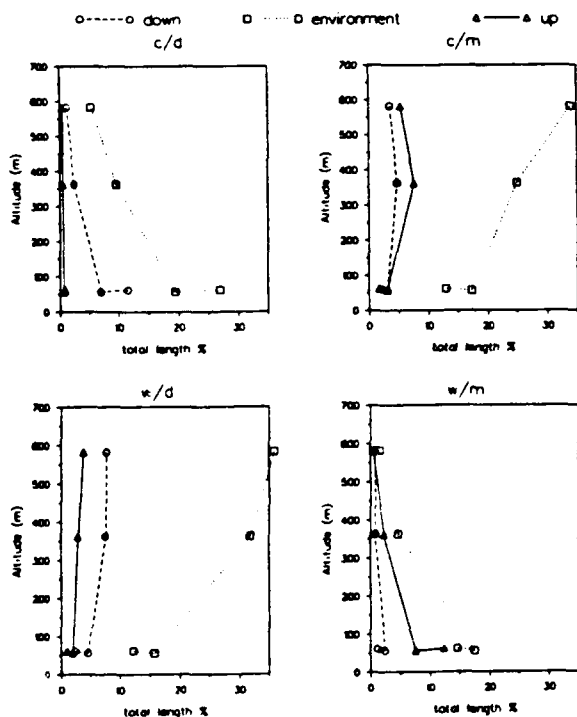


Fig. 5. Fraction of record occupied by cool/dry (C/D), cool/moist (C/M), warm/dry (W/D) and warm/moist (W/M) events in the clear region.

with  $O_3' < 0$ . When taken together, the result is a mean  $O_3'$  for updrafts that is near zero.

## 5.2 Entrainment Events

The thermodynamic classification of events enables the conditional sampling of entrainment events. In this way we look for evidence of cloud-top entrainment instability.

The fraction of record occupied by events that are cool and dry (C/D), cool and moist (C/M), warm and dry (W/D), and warm and moist (W/M) is shown in Figs. 5 and 6 for clear and cloudy regions, respectively. Statistics for events that occur exclusive of updrafts and downdrafts are included and labeled as environment.

In the absence of clouds, entrainment will produce W/D parcels. This is confirmed in Fig. 5. Updrafts near the surface are mostly W/M, changing to C/M higher up as parcels cool adiabatically. Events with vertical velocities smaller than the updraft and downdraft thresholds give properties for the environment state that mirror the dominant updraft and downdraft classes. These characteristics for the clear region are similar to what has been observed in other clear boundary layers.

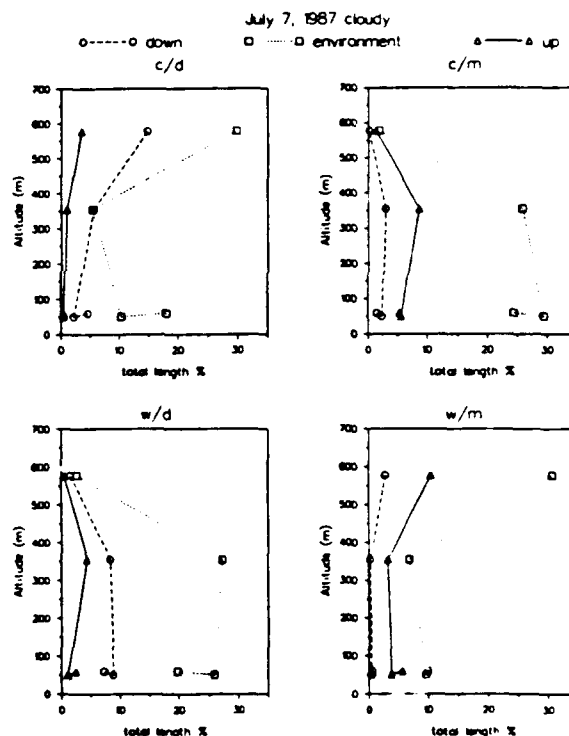


Fig. 6. As in Fig. 5 but for the cloudy region.

Near cloud top in the cloudy region the dominant downdraft type is C/D (Fig. 6). These downdrafts have large positive  $u'$  and  $O_3'$  perturbations, confirming that they are parcels entrained from above the inversion. Liquid water content for these drafts is about 20% smaller than the mean at this level. Could these events be evidence of CTEI? Nicholls (1989) also identified C/D events in a MSc layer using conditional sampling. However, for his data the jumps in equivalent potential temperature and total water mixing ratio across the inversion meant that entrainment could only produce W/D events. Nicholls argued that the C/D events he observed resulted from the collection of radiatively cooled parcels into downdrafts

occurring between cells produced by updrafts spreading out under the inversion.

An evaluation of the equivalent potential temperature and total water mixing ratio jumps for our data shows that entrainment can produce negatively buoyant parcels. The strongest evidence that evaporative cooling is responsible for the C/D events is that the perturbation mean droplet size is positive. Since smaller droplets evaporate first, an evaporatively cooled parcel will have its droplet spectrum shifted to larger sizes.

It was noted above that MSc decks have been observed to persist despite the existence of CTEI. We seek insight into why the cloud layer under investigation was maintained even though entrainment was producing negatively buoyant parcels. Conditions at cloud base offer some additional information of interest. The fractional area of C/D downdrafts at cloud base is much reduced from the value near cloud top (Fig. 6). Apparently most have become W/D downdrafts indicating that there is a weak stable region near cloud base. (There is evidence for a stable layer near cloud base in a sounding made subsequent to Fig. 1.) These W/D downdrafts still have positive  $u'$  and  $O_3'$  perturbations, indicating they contain entrained air, and have slightly positive buoyancy. There are about half as many C/D downdrafts at cloud base as W/D downdrafts. They have a substantial negative buoyancy and a downward velocity that exceeds that for C/D downdrafts found higher up. Thus, although the more prevalent W/D downdrafts produce a negative buoyancy flux, the C/D downdrafts produce a positive flux that is five times as large (Fig. 7).

The mean buoyancy flux (Fig. 2) in the cloud region is minimum at cloud base. Nicholls (1984) suggested that a small buoyancy flux signals a decoupling of cloud and subcloud layers since only a small fraction of the turbulent kinetic energy generated in the cloud layer is exported downward. In fact, Fig. 7 shows that C/D downdrafts are still generating a substantial flux at cloud base. So contrary to the implications

of the mean buoyancy flux profile, the kinetic energy generated by CTEI is affecting the entire boundary layer.

There is further supporting evidence for the free exchange between subcloud and cloud layers in the updraft statistics. The dominant updraft type at cloud base is C/M while in the cloud layer it is W/M. Both have negative  $u'$  and  $O_3'$  perturbations suggesting that the W/M updrafts are C/M updrafts after condensational heating. It is the moisture carried by these drafts that counteracts the drying effect of entrainment and allows the cloud layer to be persist even while CTEI is present.

## 6. CONCLUSIONS

We have found direct evidence that in the cloudy region investigated here, evaporative cooling of entrained parcels produced negatively buoyant downdrafts that reached down into the subcloud layer. According to the theory of cloud-top entrainment instability, the resultant drying should cause the cloud layer to breakup. Apparently this drying effect is compensated for by moisture supplied from below cloud base. To some degree this mixing across cloud base may be induced by the sinking and overturning of the evaporatively cooled parcels. This mixing takes place despite indications in the mean buoyancy flux profile that the cloud layer was decoupled.

Our results agree with the modeling work of Siems et al. (1989) who showed that although evaporative enhancement of entrainment can occur, it does not lead to cloud breakup unless the cloud layer is cut off from a moisture supply from the surface.

Data from other FIRE missions are being studied. Observations such as these of the small-scale processes in cloud-top boundary layers will aid in modeling and prediction of MSc by providing constraints for models of the breakup process.

## 7. ACKNOWLEDGMENTS

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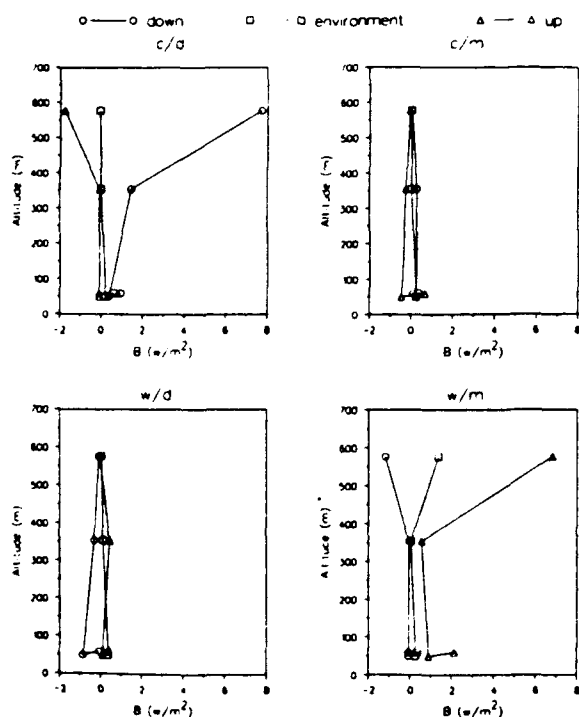


Fig. 7. Buoyancy flux produced by the various classes of events in the cloudy region.